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EFFICIENT ARC SIMULATION IN HIGH-VOLTAGE CIRCUIT BREAKERS USING THE EQUAL EMISSION BANDING METHOD

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Abstract. Accurate high-voltage arc simulation is vital for optimizing circuit breakers, critical for power grid protection. Complex arc phenomena, especially radiative heat transfer, pose significant computational challenges. This paper validates the Equal Emission Banding (EEB) method for efficient radiation transfer in switching arcs. The method balances accuracy and computational time, improving precision without significant overhead. This advancement is expected to aid future research.

Keywords: high-voltage gas circuit breakers, arc simulation, radiative heat transfer, equal emission banding, discrete ordinates method, computational fluid dynamics.

1. Introduction

The dependable operation of modern electrical power grids relies critically on the robust performance of switchgear equipment, particularly High-Voltage Circuit Breakers (HVCBs). These essential components safeguard the grid by interrupting high fault currents, a process that inherently generates intense thermal arcs. Effective arc plasma cooling is paramount for successful current interruption [1], involving complex physical and chemical mechanisms such as thermal conduction, convection, and recombination [2]. Among these, radiative heat transfer plays a particularly crucial role in dissipating energy within engineering plasmas like switching arcs [3, 4]. Consequently, accurate radiation modeling is indispensable for the design and optimization of HVCBs.

However, the precise solution of the Radiative Transfer Equation (RTE) presents a significant computational challenge. Traditional exact methods, such as the Line-by-Line (LBL) approach, necessitate extensive integration across the frequency spectrum, often requiring calculations for hundreds of thousands of wavelengths [5, 6]. While LBL offers the highest accuracy, its computational cost renders it prohibitive for practical, high-fidelity switching arc simulations. This computational burden often forces engineers to rely on simplified models, which may compromise the accuracy of critical design parameters. This inherent bottleneck underscores the critical need for efficient approximate methods that can accelerate calculations without compromising accuracy significantly. Such methods are vital for enabling comprehensive parametric studies and iterative design improvements that are otherwise impractical.

This paper addresses these computational challenges by presenting the application and validation of the Equal Emission Banding (EEB) method for efficient radiation transfer calculations in high-voltage switching arc simulations. The EEB method is a novel banding technique that fundamentally differs from conventional approaches by defining frequency bands based solely on equal blackbody emission contributions at a characteristic arc temperature, rather than relying on detailed gas absorption spectra or pressure [7]. This is achieved by utilizing the Planck function (Equation 1), which describes the spectral radiance of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature per unit area and unit solid angle [8].

$$B_\upsilon = \frac{2h}{c^2}\frac{\upsilon^3}{e^{\frac{h\upsilon}{k_B T}} - 1} \tag{1}$$

This independence from material-specific spectral properties enhances its broad applicability across various gases and operating conditions. The inherent efficiency of the EEB method, coupled with its straightforward implementation within Computational Fluid Dynamics (CFD) software like ANSYS Fluent, positions it as a highly suitable and practical solution for engineering simulations. The comparison of the EEB method with other banding methods is investigated [7]. This balance is paramount for developing next-generation HVCBs that are both effective and cost-efficient, contributing to more sustainable and resilient power grids.

2. Methodology

2.1. Arc Simulation and Computational Fluid Dynamics (CFD) Model

The numerical modeling of plasma and flow field aerodynamics within High-Voltage Circuit Breakers (HVCBs) forms the core of our arc simulation. For the simulations, ANSYS Fluent software [9] was employed as the flow solver.

The computational domain adopted the geometry of the Aachen nozzle, configured as a 2D axisymmet-

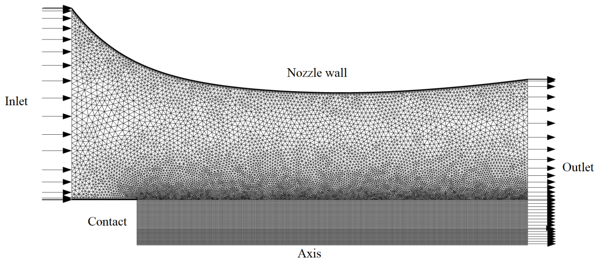

Figure 1. Computational domain of the Aachen nozzle.

ric model under steady-state conditions (Figure 1). The numerical solution was achieved by solving the Reynolds-Averaged Navier-Stokes (RANS) equations to capture the arc dynamics. The two-equation $k - \epsilon$ turbulence model was employed to account for turbulent effects. While this method is commonly used in high-speed flow fields [10] and arc in nozzle simulations [3] due to its effectiveness in capturing complex turbulence characteristics, it requires customization for accurate application to arc plasma environments. The specific details of these modifications and their implementation are thoroughly presented in [3]. Material properties for SF_6 gas were obtained from established literature sources [2, 11, 12]. The overall model setup, encompassing governing equations and boundary conditions, maintained consistency with previous research conducted on nozzle arcs [13]. Mesh generation involved a combination of structured and unstructured elements, meticulously sized to accurately resolve the severe temperature gradients present within the device, ensuring consistent mesh resolution within the boundary layer and the arc zone.

2.2. Radiation Model: Discrete Ordinates (DO) Method and Equal Emission Banding (EEB)

Accurate modeling of radiative heat transfer is fundamental to obtaining reliable results in arc simulations. The Discrete Ordinates (DO) radiation model was utilized to solve the Radiative Transfer Equation (RTE). This method discretizes the RTE across a finite number of solid angles and frequency bands, subsequently solving transport equations for radiant energy within each specified wavelength band [6, 7]. For the angular discretization in this study, parameters were set to $\theta = 5$ and $\phi = 5$ for the DO directions, and scattering effects were considered negligible [14].

The Hybrid mean method was employed to determine the Mean Absorption Coefficient (MAC) within each wavelength band [7]. This involved averaging absorption over 57 and 116 bands of the spectrum, a choice made to ensure accurate representation while simultaneously optimizing computational efficiency.

The Equal Emission Banding (EEB) method is introduced to significantly enhance the efficiency of radiation transfer calculations [7]. Its novelty stems from defining frequency bands based on equal contributions to blackbody emission, rather than employing uniform frequency intervals or relying on the gas's absorption spectrum. The process for implementing the EEB method involves the following steps [7]:

1. Selection of Control Temperature (T_c): A control temperature (T_c) is selected, typically corresponding to the maximum temperature of the arc column. For all cases in this study, a control temperature of 20,000 K was considered.

2. Determination of Band Boundaries: Determination of Band Boundaries: Band boundaries are determined by dividing the total blackbody emission power ($F(n\lambda T)$) into equal shares across the desired number of bands.

3. Adjustment of Band Widths: To prevent the formation of excessively large bands, a reference bandwidth, derived from a uniformly divided frequency spectrum, is utilized. Any band exceeding four times this reference bandwidth is iteratively divided into two equal-sized sub-bands until all bandwidths fall within the specified limit.

4. Calculation of Mean Absorption Coefficient (MAC): The MAC within each defined band is calculated using background data on absorption coefficients [11, 12] at 10 *bar* pressure. For substantially more accurate results, especially with a limited number of bands, the Rosseland and Hybrid averaging methods are recommended over the Planck method. The hybrid MAC is a weighted combination of Rosseland and Planck values, designed to balance their respective strengths and weaknesses [7].

The Hybrid mean absorption coefficient (κ_H) was employed to determine the Mean Absorption Coefficient (MAC) within each wavelength band. This method combines the Planck mean absorption coefficient (κ_P) and the Rosseland mean absorption coefficient (κ_R) to provide a more balanced representation of radiative properties, particularly in non-isothermal and optically varying media. The coefficients 0.95 and 0.05 are not universal constants. They represent semi-empirical weighting factors chosen for this specific application. This is an empirical approach, and its formula can be adjusted through calibration to achieve more accurate results. The formulas for these mean absorption coefficients are given by:

$$\overline{\kappa_P} = \frac{\int_{\upsilon_i}^{\upsilon_{i+1}} \kappa_\upsilon B_\upsilon \, \mathrm{d}\upsilon}{\int_{\upsilon_i}^{\upsilon_{i+1}} B_\upsilon \, \mathrm{d}\upsilon} \tag{2}$$

$$\frac{1}{\overline{\kappa_R}} = \frac{\int_{\upsilon_i}^{\upsilon_{i+1}} \frac{1}{\kappa_\upsilon} \frac{\mathrm{d}B_\upsilon}{\mathrm{d}T} \, \mathrm{d}\upsilon}{\int_{\upsilon_i}^{\upsilon_{i+1}} \frac{\mathrm{d}B_\upsilon}{\mathrm{d}T} \, \mathrm{d}\upsilon} \tag{3}$$

$$\overline{\kappa_H} = 0.95\overline{\kappa_R} + 0.05\overline{\kappa_P} \tag{4}$$

where κ_ν is the spectral absorption coefficient, $B_\nu(T)$ is the Planck function at frequency ν and temperature T. This involved averaging absorption over

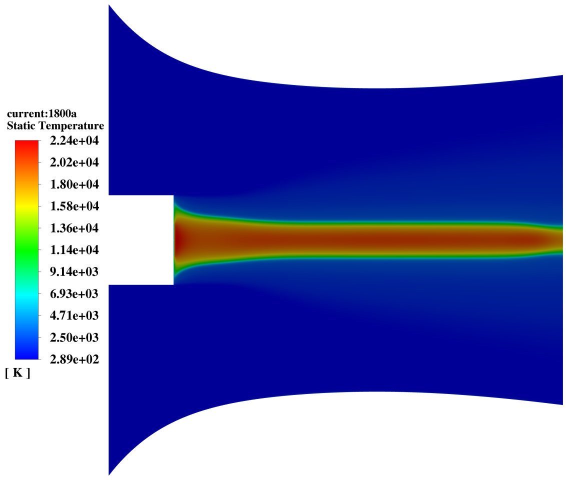

Figure 2. Simulated temperature contours for the 1800A SF_6 arc in the Aachen nozzle.

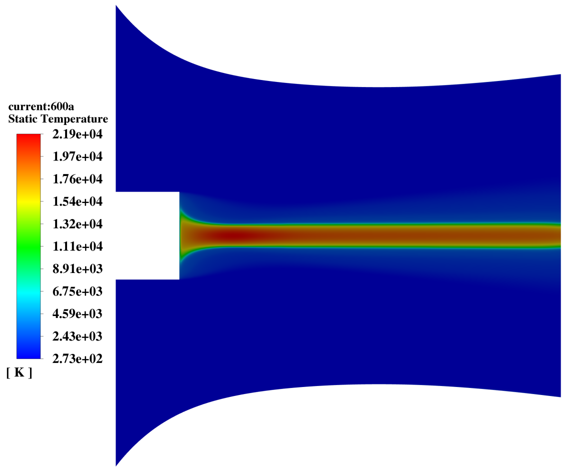

Figure 3. Simulated temperature contours for the 600A SF_6 arc in the Aachen nozzle.

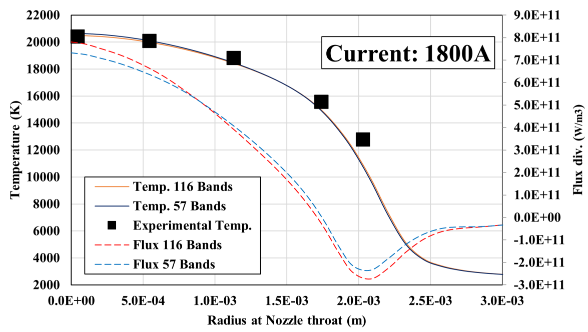

Figure 4. Comparison of simulated and experimental temperature profiles and radiation flux divergence for 1800A SF_6 arcs at the nozzle throat.

57 and 116 bands of the spectrum, a choice made to ensure accurate representation while simultaneously optimizing computational efficiency.

This automated banding algorithm, implemented in C++, requires only the control temperature and the desired number of initial bands as inputs. All Mean Absorption Coefficients (MACs) were calculated for each band across a temperature range of 300 K to 35000 K. The resulting data was then incorporated into ANSYS Fluent software via a User-Defined Function (UDF), enabling its use in the simulations.

3. Results and Discussion

3.1. Validation of Simulation Setup

The reliability and accuracy of the established simulation setup were rigorously verified through a comprehensive comparison with experimental data. For this validation, the 1800A and 600A SF_6 arc case within the Aachen nozzle geometry, simulated under steady-state conditions. The computational results were directly compared against the well-established experimental measurements reported by Leseberg and Pietsch [15, 16].

The temperature contours for the 1800A and 600A arc cases in the Aachen nozzle were generated and compared, as shown in Figures 2 and 3, respectively.

A strong and consistent correlation was observed between the simulated and experimental temperature profiles along the nozzle throat. For the 1800 A arc case, the average relative error in the temperature profile was found to be 1.45% with 57 bands and 1.35% with 116 bands. Similarly, for the 600 A arc case, the average relative error was 5.1% with 57 bands and 5.3% with 116 bands. This agreement was especially pronounced in regions characterized by rapid temperature gradients, such as those near the arc edge. The accurate capture of these steep gradients is critical, as they dictate the energy dissipation mechanisms and overall arc behavior. This detailed validation confirms the model's capability to accurately represent the complex physical phenomena governing arc cooling and dynamics within HVCBs.

The validation of the temperature profiles in the nozzle throat with experimental data was successfully demonstrated using the Equal Emission Banding (EEB) method with just 57 bands, as illustrated in Figures 4 and 5 for both cases. These results show a very close agreement with the experimental data, even with this significantly reduced number of bands.

The demonstrated ability of ANSYS Fluent to precisely capture these intricate processes provides a robust foundation and crucial confidence for the subsequent application and evaluation of the Equal Emission Banding (EEB) method in our study. This validated framework ensures that any observed improvements or efficiencies stemming from the EEB method can be reliably attributed to the radiation model itself, rather than inaccuracies in the underlying CFD setup.

Furthermore, by employing the Discrete Ordinates (DO) method in conjunction with the non-gray gas banding provided by the EEB approach, it was pos-

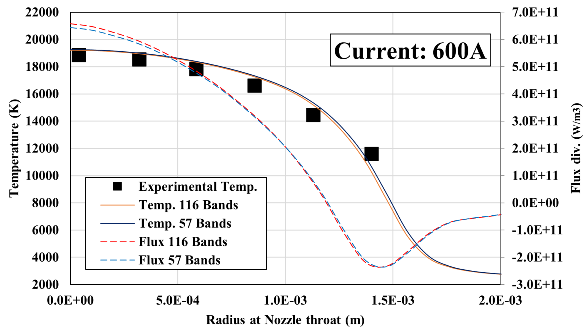

Figure 5. Comparison of simulated and experimental temperature profiles and radiation flux divergence for 600A SF_6 arcs at the nozzle throat.

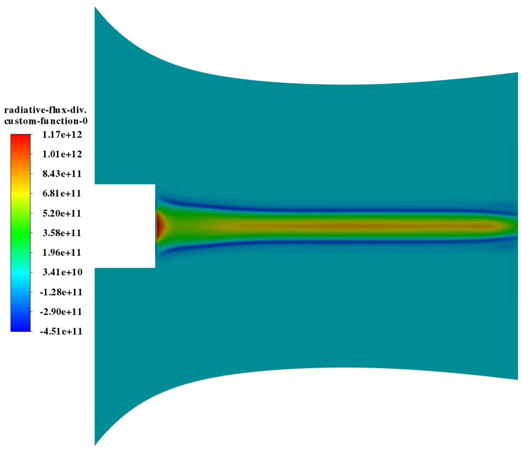

Figure 6. Radiation flux divergence across the computational domain for the 1800A SF_6 arc.

sible to accurately calculate the radiation flux divergence. These results for the radiation flux divergence at the nozzle throat are presented in Figures 4 and 5. As depicted in the figures, this approach allows for the precise identification of both the emission and absorption areas of the arc's column. The ability to analyze and investigate the radiation flux divergence throughout the entire computational domain is highly valuable (figure 6). This detailed insight into energy transfer due to radiation is crucial for the optimal design of HVCBs and for precise control of nozzle ablation, contributing significantly to the overall performance and longevity of HVCBs.

3.2. Impact of Band Number: 57 vs. 116 Bands

A critical advantage of the Equal Emission Banding (EEB) method lies in its remarkable ability to achieve acceptable accuracy with a relatively low number of frequency bands. It was observed that the internal banding criterion, which includes an iterative division process to prevent excessively large bandwidths, slightly increased the final band count. For instance, an initial setting of 50 bands typically resulted in 57 final bands, while 100 initial bands yielded 116 final

Criteria	**1800A**	**600A**
Temperature profile	3.1	0.2
Radiative flux div.	8.9	3.4

Table 1. Average relative error (%) for the variations in criteria at the nozzle throat for simulated SF_6 arc using 57 and 116 bands.

bands. In this part, the efficiency of the EEB method has been assessed for two initial band numbers (50 & 100), which consequently led to finding a balance between accuracy and time of computing.

A key objective of this investigation was to demonstrate that utilizing as few as 57 bands provides sufficient accuracy for engineering applications. To quantify this, we performed a detailed comparison of the average relative error of the temperature profiles in the nozzle throat and the peak temperatures at the arc center for both the 1800 A and 600 A SF_6 arc cases when using 57 bands versus 116 bands.

Table 1 provides a summary of the average relative error in these key temperature profiles when transitioning from 116 bands to 57 bands. The data presented in this table clearly indicates that the temperature profiles are remarkably close, validating the sufficiency of 57 bands for accurate temperature prediction.

Furthermore, radiative flux is highly sensitive to temperature changes, making its accurate prediction crucial for arc simulation. We meticulously compared the radiative flux in the nozzle throat across different band numbers. Figures 4 and 5 illustrate the variation of radiative flux divergence. The relative changes for radiative flux divergence are also included in Table 1, demonstrating that even with a reduced band count, the flux results remain highly consistent.

For the 1800 A case, further comparisons were conducted for the potential and temperature along the arc axis, specifically evaluating the performance between the 57 and 116 EEB band configurations. As presented in Figures 7 and 8, the variation between the results obtained with 57 bands and 116 bands was found to be negligible. The average relative error for the potential on the axis was 3.5%, and for the temperature on the axis, it was 0.3%. These results highlight the robustness of the EEB method, demonstrating that a reduced band count of 57 can maintain high fidelity for these critical arc characteristics without significant loss of accuracy compared to a higher band count.

Beyond accuracy, the computational benefits of employing 57 bands are significant. The proposed method enables radiation calculations to be performed over **2 times faster** when using 57 bands compared to 116 bands, with the observed change in results being negligible. Specifically, the simulations with 57 bands converged in approximately 1 day, utilizing 20 CPU cores and 1 GPU for parallel computing acceleration. In contrast, the 116 bands case required

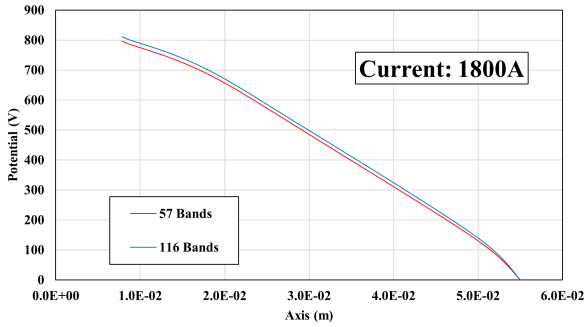

Figure 7. Comparison of potential in the center for 1800A SF_6 arc.

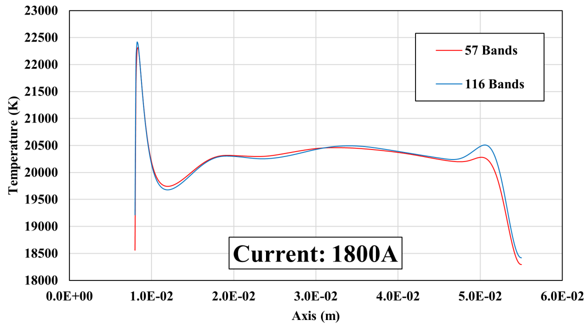

Figure 8. Comparison of peak arc center temperatures for 1800A SF_6 arc using 57 and 116 bands.

approximately 2.5 days to converge under the same computational resources. This ease of integration, combined with the demonstrated accuracy and significant speedup, strongly reinforces that 57 bands are indeed sufficient for practical arc simulations in engineering applications, offering reliable results and affordable computational cost.

4. Conclusions

This paper successfully presented and validated the Equal Emission Banding (EEB) method as an efficient and practical solution for accurate radiative heat transfer calculations in high-voltage switching arc simulations, critical for High-Voltage Circuit Breaker (HVCB) design.

Our rigorous validation against experimental data for 1800 A and 600 A SF_6 arcs in the Aachen nozzle demonstrated strong correlation in temperature profiles, with remarkably low average relative errors (1.45% for 1800A and 5.1% for 600A with 57 bands). Further comparisons for the 1800A case showed negligible variation in axial potential (3.5% error) and temperature (0.3% error) between the simulated results obtained with 57 bands and those with 116 bands, confirming the robustness of our setup and radiative simulation by 57 bands.

A key finding is the effectiveness of the EEB method with a significantly reduced band count. Comparative analysis between 57 and 116 EEB bands revealed that 57 bands provide acceptable accuracy for practical engineering applications, showing negligible differences in predicted temperature profiles, peak arc center temperatures, and radiative flux divergence. This reduction yields substantial computational benefits: 57-band simulations converged over 2 times faster (approx. 1 day vs. 2.5 days with 20 CPU cores and 1 GPU).

The integration of the Discrete Ordinates (DO) method with EEB's non-gray gas banding enabled precise calculation and identification of emission and absorption areas of the arc column. This detailed insight into radiation flux divergence is invaluable for optimal HVCB design and precise nozzle ablation control. A significant advantage of the EEB method is its independence from material properties, meaning that fluctuations or specific values of the absorption coefficient do not affect its banding process. This, coupled with its straightforward and rapid banding generation, makes it highly versatile.

In conclusion, the EEB method offers an efficient and accurate approach for modeling radiative heat transfer in high-voltage switching arcs, striking a crucial balance between computational cost and reliable results. This advancement significantly contributes to HVCB optimization and more sustainable engineering practices, aiding future studies in this field.

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